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Abstract

The objective of this paper is to analyze the sensitivity to surface soil parameters of very high resolution TerraSAR-X radar data taken over bare soils, and to study the spatial variability of these parameters at a fine scale (within a field plot). The relationship between the backscattering coefficient and the soil's parameters (moisture, surface roughness, texture and local topography) was examined by means of four satellite images, as well as ground truth measurements, of each of three agricultural plots, recorded during several field campaigns in the winter and spring of 2008. TerraSAR images demonstrate high potential for the identification of local variations of roughness and texture. An approach for the estimation of local moisture is proposed, using an empirical method adapted to the scale of an individual field. The results show that by using TerraSAR-X data to study bare agricultural fields, local variations in soil moisture can be retrieved with an RMS error of 0.05 cm^3.cm^{-3}.

Index terms- soil moisture, roughness, soil texture, TerraSAR-X images, within field plot scale.

I. Introduction

The knowledge of soil surface conditions, soil moisture content and roughness is of the highest importance in agriculture and vegetation growth monitoring, atmospheric sciences and hydrological studies [1-2]. Only remote sensing from space allows soil surface

conditions to be monitored over large areas at regular intervals. Therefore, considerable efforts have been devoted to the use of active microwave remote sensing techniques, in order to measure the superficial soil characteristics of natural surfaces from space [3-8].

For bare soils, the radar signal, which depends on various radar parameters (incidence angle, frequency and polarization), is correlated to surface roughness, soil moisture content, and to a lesser extent to the soil's textural composition [9]. Surface soil parameters have been estimated over large scales from space (> 100 km²), using several synthetic aperture radars (ERS-1/2, SIR-C, RADARSAT-1, ASAR/ ENVISAT,…) or scatterometers (ERS, ASCAT, QUICKSCAT, …).

Over the last decades, various electromagnetic backscattering models (Kirchoff models, the small perturbation Model, the Integral Equation Model (IEM), AIEM, …) have been developed in order to estimate these parameters ([10-11], …). In practice, it is still difficult to identify a single model with a large domain of validity, for real agricultural soils, in spite of the improvements achieved over the past few years [12-14]. Various improvements have also been achieved in the description of roughness, by introducing multi-scale approaches, generalized power law spectra, Zs parameter and other methods [15-20].

Studies using simulation models or experimental analysis have shown that the radar signal is more sensitive to surface roughness at high incidence angles, than at low incidence angles [21]. Furthermore, the dependence of the backscattered radar signal on surface roughness in agricultural areas is significant mainly for low levels of electromagnetic roughness, in particular as characterised by the *k.s* parameter (*k*: wave number, s: root mean square height) [21-22]. Discrimination between various roughness classes is thus significantly better at higher radar wavelengths (the L-band provides better results than the C- or X-bands).

Studies dealing with the estimation of soil moisture can be separated into two spatial scales: regional or global scales, and agricultural field plot scales (~0.5 km²). At the regional scale, different authors [23-25] have attempted to estimate soil moisture content only, by neglecting the influence of roughness. A linear relationship between surface moisture and backscattered radar signals has been proposed. The uncertainty of the retrieved soil moisture in these studies is approximately equal to 0.04 $cm^3.cm^{-3}$. This approach has been validated by a large number of experimental studies, and is generally considered to provide a valid approximation for a given studied site. However, the coefficients needed to describe the linear relationship often vary from one region to another and also from one year to

another, in particular in the presence of roughness variations during moisture monitoring [26].

At the scale of an agricultural field, the roughness effect cannot be neglected. Different studies have focused on coupling the data from different configurations (incidence angles, polarizations, frequencies) in order to retrieve roughness and moisture simultaneously ([18], [22], [27-31]). Other analyses implement an approach involving the detection of changes, whilst making the hypothesis that one parameter is stabilised ([24], [32]).

As a consequence of speckle effects, and typical spatial resolutions of around 20 m, spatial variations within a field plot were very rarely analysed using radar remote sensing. In fact, with classical SARs, such small-scale variations could not be observed or analysed. With the arrival of new sensors, in particular TerraSAR-X, which provides data with a resolution of 1 m, it has become possible to analyse roughness, moisture and soil composition variations at a finer scale (within a field plot).

In this paper, we propose to analyze the contribution of high spatial resolution X band TerraSAR-X data to the local estimation of three soil surface parameters: soil moisture, roughness and soil composition, of several bare agricultural field plots at the within field scale. The paper is organised as follows: (i) presentation of the study area and data set, (ii) examination and discussion of the results, (iii) concluding remarks.

II. Data set and SAR data

A. Radar data

Four TerraSAR-X images (~9.65 GHz) were acquired at low incidence angles (26°), since the volumetric soil moisture can be estimated more accurately at low and medium incidence angles, with minimal influence from the soil surface roughness, than at high incidence angles. The images were taken with a horizontally polarized beam, with a ground pixel spacing of 1m.

Radiometric calibration of TerraSAR-X images was carried out in using Fritz [33]

$$\sigma_i^0(dB) = 20\log_{10} DN_i + 10\log_{10}(CalFact) + 10\log_{10}(\sin(\theta_i)) \quad (1)$$

where σ_i^0 is the backscattering coefficient for pixel i, DN_i is the i^{th} digital number (amplitude of the backscattered signal), and CalFact is the calibration coefficient (scaling gain value), which varies within the range: 10^{-6} to 10^{-4}, depending on radar incidence angle (θ_i) and polarization. All radar images were then geo-referenced using aerial orthophotographs.

B. The Orgeval site

The Orgeval watershed (104 km²) is a sub-catchment of the Grand Morin watershed (1070 km^2), and is located 70 km to the east of Paris (latitude 48°47' to 48°55'N, and longitude 3°00' to 3°15'E). It is an experimental basin for hydrological research, managed since 1963 by the Cemagref research institute. Most of the watershed is relatively flat, is affected by a degraded oceanic climate, and is also subject to the semi-continental influence of the East of France. Its mean annual rainfall is 706 mm. Most of this watershed is covered with a silt loam: 17% clay, 78% silt, 5% sand, characterized by a low permeability. As textural characteristics are homogeneous throughout the basin, the main heterogeneous feature of Orgeval is the vegetation which covers the soil, which varies each year. Agriculture activities occupy 80% of the watershed surface. The main crops are wheat, corn, peas and barley. The remaining crops are colza, flax and sugar beet.

C. Ground truth measurements

The field campaigns presented in this study were carried out on 13th and 15th February, 30th April and 15th May 2008. In February, field campaigns were carried out one week after strong rain period (Figure 1). Soil was still wet, because of winter time, but soil surface was drying up due to influence of solar radiation and wind. In April, field campaigns were carried out during rainy event. Therefore, soil was homogenously wet. Finally, in May, measurements were carried out 12 days after the last rain, and soil was very dry.

Simultaneously with the radar measurements, ground truth measurements of soil roughness, moisture content and bulk density were carried out on three field plots. The number of field plots ranged from 6 to 12, for all campaigns. In this study, we will discuss the results of only three bare agricultural fields: Fields P1, P9 and P11. For these three fields, a Digital Terrain Model (DTM) was established using a differential GPS, used with a horizontal resolution of 50 m, in order to analyse local variations of topography within the scale of the fields (Figure 2) of which those used for agriculture are rather flat.

Gravimetric soil moisture samples were collected as a function of agricultural plot size: about 10 to 20 localized samples were taken per field, at depths in the range 0–5 cm. The gravimetric soil moisture content was calculated by drying the samples at 105°C for 24 h. The volumetric soil moisture (M_v) was then obtained by multiplying the gravimetric soil moisture by the bulk density. Three to five bulk density measurements were made for each plot site, using 9 cm long cylindrical samples with volumes of 500 cm^3. The lower values of bulk density corresponded to recently tilled fields, whereas higher values were found for the untilled fields. The soil moisture measurements used in this study were measured within 2 hours of the radar acquisition, and the volumetric soil moisture was derived from

$$M_v = \left(\frac{\theta_{wet} - \theta_{dry}}{\theta_{dry}} \right) \cdot \rho_b \qquad (2)$$

where θ_{wet} and θ_{dry} are the wet and dry sample weights, respectively, and ρ_b is the dry soil bulk density.

Table 1 illustrates the mean values of soil moisture over the studied fields, for all of the campaigns. We note that the driest measurements correspond to the 13th of May, and the wettest measurements to February and April (winter and rainy period, respectively), as shown in Figure 1.

Roughness measurements were made using a pin profiler (with a total length of 1 m and a resolution of 2 cm). In order to guarantee suitable precision in the roughness computations, about 10 profiles were recorded for each field. As the surface height profile is considered to be ergodic and stationary, we can compute the correlation function for each profile ([9]), and derive two statistical parameters: the rms height (vertical scale of roughness), and the correlation length (l) which represents the horizontal scale over which similar roughness conditions are detected. **The rms height values varied between 0.55 and 3.29 cm, for all fields and all campaigns, with k.s thus varying between 1.1 and 6.64 (k: wave number).** The correlation length varied between 2.28 and 9.20 cm (Table 1). **Although a large number of profiles was considered, because of the high resolution (2 cm) corresponding to the spacing between two successive pins and limited profile length, the accuracy error of the roughness estimations could be higher than 10%, particularly for low correlation lengths ([34-36]). For the measurements made in February, we retrieved only high roughness soils (*rms*>1.5cm). For the measurements made in May, we have only smooth and medium roughness fields (*rms*<1cm).**

III. Results

A. Backscattered signal in agricultural field plot

In Figure 3 the backscattered signal has been plotted for each agricultural field, on all dates. Over-all, it can be observed that the signal is quite similar for plots 1, 9 and 11 in February, which is a wet period of the year (0.33 $cm^3.cm^{-3}$ mean soil moisture), with backscattered values from 0 to -10 dB. In May, the soil is dry (0.17 $cm^3.cm^{-3}$ mean soil moisture), and the smallest backscattered values are observed (-10 to -15 dB). However, we can distinguish heterogeneities within field plots: (i) P11 the 13th and 15th February, (ii) P11 the 13th of May, and (iii) P1 the 30th April, which will we discussed in more detail in the next sections.

B. Backscattered signal function of roughness

In spite of the fact that the images where taken at low incidence angles, where the influence of the soil surface roughness is minimal, the roughness effect can be clearly distinguished in the TerraSAR-X images [37]. For instance, P1 the 30th April had two distinct soil roughness values (Figure 3), because of the sowing period where P1 was only half **tilled**. Unfortunately we have no roughness measurements at this date. For the 13/05/08 for P1 we did not observe roughness differences within field because the field plot was completely **harrowed**. Field P11 had also two distinct soil roughness values on the 13th May (Figure3), because the field had been **tilled** in different manners. The left zone of field P11 (low signal values) corresponds to a zone of low roughness (rms of 0.55 cm), whereas the stronger backscattered signal corresponds to the right part of the field (rms of 0.83 cm). In addition, this difference in soil roughness could also be observed in situ and with optical imagery (Figure 4).

C. Relationship between backscattered radar signal and soil moisture

Figure 5 shows soil moisture measurements on the 13th of February with a small heterogeneity in the different test fields. . Moreover, there appears to be no correlation with field topography (Figure 2). The surface slope was not analysed, because of the fields' very low topography and the limited horizontal resolution of used GPS. In all of the campaigns, we observed limited variations in soil moisture **(<0.1** $cm^3.cm^{-3}$**)** for each date at within field plot scale.

In the lower left part of field P11, on the 13th and 15th February (Figure 3), we can observe an anomaly zone which presents a mean backscattered signal of -7 dB and a mean volumetric soil moisture of 0.36 $cm^3.cm^{-3}$, while the left-over field plot has a mean backscattered signal of -4 dB and a mean volumetric soil moisture of 0.37 $cm^3.cm^{-3}$. **The difference in backscattered signal (3 dB) cannot be explained by the small difference in soil moisture measured in the first five centimetres between them (mean value of approximately 0.01** $cm^3.cm^{-3}$**). Nevertheless, during measurements, for this lower left section of the plot, a driest surface over the first millimetres of depth, was clearly observed. Unfortunately, the measurements were made using only a mean value of the soil moisture over the first five centimetres, without accounting for the soil's moisture profile.** Analyses of soil texture have been carried out into field P11 (Table 2 - Figure 6) to investigate this phenomenon. We observe that samples taken from this lower left part zone (a,b,d and e) present differences in soil composition, more clayey than the rest of the field with a maximum of 20**%. This difference in texture explains the difference in surface drying rate. This behaviour could explain the large difference of -3dB between the radar measurements. In fact, in the X band, radar wave penetration does not reach 5 cm, particularly for the case of high moisture contents. It is limited to less than approximately 1 cm, for a volumetric moisture of 0.3 $cm^3.cm^{-3}$ [38]. For this reason, difficulties can be encountered in the interpretation of radar signals, in cases where the vertical moisture profile varies strongly in the first centimetres.**

Furthermore, the soil texture effect disappears in the TerraSAR-X images corresponding to two different events in field P11: (i) on the 30th April, because the image was acquired during a rainy period when the soil was completely saturated, with no moisture profile effect; and (ii) on the 13th May, when the soil was dry in the first centimetres of ground measurements.

As stated in the introduction, the inversion of radar signals was, until recently, and for a large number of studies, based on a simple linear relationship between the mean signal at one incidence angle (σ^0) and the mean volumetric soil moisture (M_v):

$$\sigma^0(dB) = a \cdot M_v(\%) + b \qquad (3)$$

where *a* and *b* are coefficients depending on incidence angle, roughness and polarization.

The mean backscattered radar signal has been calculated within a 3 m radius of the location of each soil moisture sample (to avoid speckle effects), on all sampling dates. An increase in backscattered signal is observed when the soil moisture increases from 0.15 to 0.35 $cm^3.cm^{-3}$.

The contribution of surface roughness to the backscattering of radar signals is significant, and cannot be neglected, if we consider relationship between moisture and radar signal at the scale of a field [37], [39]. In the present case, we observe small roughness values on the dry dates and high roughness values on wet dates. Therefore, before attempting to analyse the moisture content, we propose to eliminate the roughness effect on radar measurements over the three tested fields. In Equation (3), the effect of roughness is present in the parameter "b". The parameter "a" is independent of roughness, if we consider a studied site with a uniform roughness between moisture measurements. This additional influence of roughness and moisture can be demonstrated by different theoretical simulations [18].

However, roughness effect is also included in the slope parameter "a" if the roughness is not stable between measurements.

In order to eliminate the roughness effect, we first attempted to identify the slope parameter "a" in the case of a stable roughness. The estimated value of this parameter could be considered constant for the purposes of our study, for a given incidence angle and radar frequency. In order to have stable roughness parameters for different moisture values, we propose to include, with the radar measurements, theoretical simulations using the numerical moment method. This is based on the solving of integral equations over simulated surfaces respecting roughness and dielectric constant characteristics, with no physical approximations ([40-41]).

Different studies have demonstrated the agreement between real radar signals and theoretical surface backscattering models for the case of low roughness and high moisture content ([42-43]). In fact, in the present surface type, we have no multi-scattering or volume diffusion effects, due to the limited penetration of the waves. We thus attempt to retrieve the parameter "a" from the real data and simulations, for small representative roughness values estimated in test fields on the 13th of May. As we have real radar data for dry soil conditions only, we then include simulations for the case of high moisture contents. We thus use a numerical approach with the moment method, in order to simulate radar signals for low values of roughness and high moisture levels. After adding these simulated values, the mean backscattered radar signal is plotted for each agricultural field as a function of the mean soil moisture in each respective field (Figure 7). The derived empirical model establishes, for HH polarized radar signals and at incidence of 26°, a linear relationship between soil moisture and the backscattering coefficient, with a high R^2 (0.91). **The slope of this relationship is independent of roughness; in fact we consider the same roughness value with the same number of fields, on dry and wet dates.**

In order to estimate soil moisture at the local scale, using TerraSAR-X data, we propose to use the field scale derived relationship (Eq. 3) at local scales. **For each field, we establish a relationship using the same slope and roughness, corresponding to an offset (b parameter), computed directly from the real radar data and ground moisture values estimated on the same date.** In order to validate our approach, Figure 8 provides a comparison between the soil moisture values computed from different ground truth samples, and the retrieved soil moisture values found by inverting the mean of the radar signals recorded inside a 3m radius of the moisture sample locations. **This allows retrieving soil moistures with a RMSE of 0.05**

$cm^3.cm^{-3}$, which corresponds to a good estimation at such a fine scale, in view of the probable local variations in roughness and topography. In fact, at the field scale, for which in experimental scientific studies we generally estimate the moisture content with an accuracy close to 0.04 $cm^3.cm^{-3}$ ([18], [31]), we average all of these effects. This method could be very useful for the estimation of irrigation requirements, particularly in arid and semi-arid regions. In fact, in these regions, we can observe very large spatial variations in the moisture content of a single field, before and after irrigation. This type of measurement could thus become a highly useful tool for the identification of areas requiring irrigation in complementarily with modelling approaches [44].

IV. Conclusions

The objective of this study was to analyze the behaviour of TerraSAR-X signal as a function of soil moisture, soil texture and surface roughness over bare fields, at a spatial resolution of 1 m. The high resolution images generated with this sensor have the advantage of revealing differences in the soil roughness, soil moisture and texture at within field plot scale even when acquired at low incidence angles (26°), where the influence of soil roughness is frequently minimal.

On the other hand, changes in soil texture could be observed within field plot. These changes where detected by a difference of 3 dB of the backscattered signal with only a 1% of difference of soil moisture. Increase of clay content (maximum 20%) produced a decrease of backscattered signal for TerraSAR-X frequency (~9.65 GHz) **due in all probability to faster drying of the first millimetres of the soil.**

In addition, an empirical approach has been proposed for the local estimation of volumetric soil moisture, using a linear expression which is shown to be valid at the field plot scale. **We propose a method which, following the removal of roughness effects, can be used for the estimation of the local volumetric soil moisture, with an RMS error equal to 0.05 $cm^3.cm^{-3}$.**

This study has shown the high potential of TerraSAR-X high resolution data, for the analysis of local variations in surface parameters, in particular soil roughness and soil moisture at the within field plot scale. It will be very interesting to analyse these effects in other regions, in particular those characterised by strong variations related to changes in topography, where we could have a more important contrast of soil moisture within field plot. Moreover, (i) it could be interesting to combine TerraSAR-X radar data with very high resolution optical data, for various precision agriculture applications, (ii) to study the differences of soil composition detected in this study and (iii) **to study irrigation management problems in arid and semi-arid regions.**

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Biography and photo for each author

Thais Paris Anguela was born in Vilanova i la Geltrú, Spain. She received the Water Sciences Ph.D. degree from the École Nationale du Génie Rural des Eaux et des Forêts (ENGREF, AgroParisTech), Paris, France, in 2004. In 2007 she joined the Centre d'étude des Environnements Terrestre et Planétaires (new LATMOS), Vélizy, France. Her research interests include microwave remote sensing applied to hydrology.

Table 1. Main characteristics of the data set at the Orgeval watershed, for each of the studied agricultural fields: incidence angle and polarisation of the TerraSAR-X images, range (mean and standard deviation) of soil moisture (M_v) and soil bulk density (ρ), together with its roughness characteristics: rms surface height (*rms*), and correlation length (*l*).

Date (dd/mm/yy)	TerraSAR-X	Field number	Range of Mv ($cm^3.cm^{-3}$)	Range of ρ ($g.cm^{-3}$)	*rms* (cm)	*l* (cm)
13/02/08	26° - HH	**P1**	0.35 ± 0.03	1.31 ± 0.08	1.78	5.43
		P9	0.31 ± 0.02	1.23 ± 0.10	2.54	4.98
		P11	0.36 ± 0.04	1.32 ± 0.14	3.29	9.20
15/02/08	26° - HH	**P1**	0.33 ± 0.02	1.31 ± 0.08	1.78	5.43
		P9	0.30 ± 0.02	1.23 ± 0.10	2.54	4.98
		P11	0.34 ± 0.05	1.32 ± 0.14	3.29	9.20
30/04/08	26° - HH	**P1**	0.33 ± 0.02	1.17 ± 0.09	-	-
		P9	0.33 ± 0.01	1.19 ± 0.10	-	-
		P11	0.32 ± 0.01	1.12 ± 0.11	-	-
13/05/08	26° - HH	**P1**	0.16 ± 0.02	1.08 ± 0.04	0.72	2.28
		P9	0.16 ± 0.02	1.20 ± 0.03	0.78	2.52
		P11	0.20 ± 0.03	1.28 ± 0.10	0.55 (left) and 0.83 (right)	2.65 (left) and 2.84 (right)

Table 2. Soil texture samples (%) for the field P11.

Soil samples	Clay (%)	Silt (%)	Sand (%)
Watershed mean	17	78	5
A	28	68	4
B	27	69	4
C	19	78	3
D	37	60	3
E	37	61	2
F	17	80	3
G	17	80	3
H	16	78	6
I	16	79	5

FIGURES

Figure 1. Observed daily precipitation (mm).

Figure 2. Topography (in meters) of the 3 agricultural fields. Black dots represent ground truth measurements of volumetric soil moisture taken on different campaign dates

Figure 3.Backscattered signal (dB) in TerraSAR-X images, and soil moisture sampling locations (black dots), for each field plot.

Figure 4. Optical image (Kompsat) of the 3 agricultural fields, taken on 13/05/08. RGB: B1, B2, B3

Figure 5. Ground truth measurements of volumetric soil moisture on 13/02/08 (black dots).

Figure 6. Field P11, soil texture samples.

Figure 7. Relationship between the mean backscattering coefficient and the mean volumetric moisture content in the top 0–5 cm of soil, for each agricultural plot (P1, P9 and P11). The low values correspond to TerraSAR data acquired on May 13, and the high values correspond to simulations with the same roughness at high moisture values. HH polarization and incidence angle of 26°

Figure 8. Comparison between the values of volumetric soil moisture (M_v), estimated from the inversion of TerraSAR-X radar data, and from *in situ* measurements.